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RESEARCH DRILLING AT INYO DOMES, CALIFORNIA: 1984 RESULTS*

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Abstract

Two core holes drilled this year at Inyo Domes, California as part of the national Continental Scientific Drilling Program intersected their assigned igneous targets. Results indicate that the northern end of the 600-year-old-dome chain is underlain by a rhyolite dike which reached the surface at Obsidian Dome and the near surface beneath Glass Creek. Under Glass Creek the intrusion is 7.3 m thick at a depth of 640 m, but 1.1 km to the north it broadens to 51 m at a depth of 440 m where it forms the conduit which fed Obsidian Dome.

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Introduction

During the 1984 field season, two research holes were cored into the Inyo chain of young rhyolite domes, which cuts across the northwest margin of Long Valley Caldera, California (Fig. 1). One hole slanted under the vent of Obsidian Dome and completely penetrated the conduit of the volcano. It was spudded on August 16 and reached its final depth on September 9. The second hole was sited along Glass Creek between Obsidian Dome and the next dome to the south, and intersected the rhyolite dike which underlies the chain. It was spudded on September 18 and reached final depth on October 28.

Both holes are part of the Inyo Drilling Program, whose goal is to determine the thermal, chemical, and mechanical behavior of silicic magma in the upper crust. Such data are essential for understanding the causes of explosive volcanism and the development of hydrothermal systems. Based largely on surface geologic evidence, an intrusion beneath the northern portion of the Inyo Chain was selected for study. This intrusion is sufficiently young to be neither thermally nor chemically equilibrated with its environment, and was emplaced in the relatively simple geologic setting of Sierra Nevada basement. Choice of a site where the crust was initially cold and where the only local eruptive event in the last 3 My is the 600 y event of interest greatly facilitates interpretation of the thermal effects of the intrusion.

The program was proposed by a consortium consisting of investigators from a number of universities, U. S. Department of Energy laboratories, and the U. S. and Canadian Geological Surveys. Funding for the drilling and much of the related research was provided by the Office of Basic Energy Sciences of DOE. Additional manpower costs are being borne by the Geological Surveys.

The drilling described here is modest by oilfield and even by geothermal standards. Its significance lies in the scientific investigation of a previously unexplored geologic environment, and in the role of the project as an early component of the Continental Scientific Drilling Program (CSDP). This and other efforts within CSDP are predicated on the belief that much of the future progress in our understanding of the Earth, including the dynamic processes of planetary differentiation and convective cooling represented by magmatism, will come from direct observations at depth through drilling. In the case of silicic magmas, which are responsible for the formation of continental crust, many of the fundamental problems can be addressed at surprisingly modest depth.

An overview of the Inyo Program can be found in EOS (Eichelberger et al., 1984). In this article we report early results of the 1984 drilling effort.

1984 Drilling Objectives

The first of the two holes was chosen to provide the shortest and surest route into the intrusive portion of the Inyo system: the conduit of the largest dome. The second hole was more ambitious in terms of both targeting and depth. It was to provide a test of the existence at relatively shallow depth of a dike proposed by Miller (1983; in press) and Fink and Pollard (1983) on the basis of structural evidence and the linear arrangement and similar ages of Inyo eruptive centers. If successful, it would sample a portion of the intrusion which did not vent to the surface.

A major objective of both holes was to compare the chemical composition, volatile content, and crystallization behavior of the intrusive portion of the Inyo system with the already well studied extrusive portion (Bailey et al.,1976; Miller, in press). Such comparisons should lead to a better understanding of a variety of magmatic processes including pressure dependence of degassing, vapor transport, and magma/wallrock/ fluid interaction. Another objective was to define the position and structure of subsurface intrusions and relate them to observed surface volcanic features. Information about the size and structure of the dike and conduit, combined with existing information about the eruptive event, should provide new insights into eruption processes and the mechanics of dike emplacement and propagation. The holes thus provide a chemical and physical link between volcanoes and the sub-volcanic regime.

Field Operation

Factors influencing the design of the field operation included the multidisciplinary and multi-institutional nature of the group, and the relative isolation of the site. Because of the remote location, it was necessary to fully document and store the core on site, after each "wellsitting" shift. The 24-hour-a day operation thus required three wellsitters, and each normally served a 10 day tour of duty. One of the three acted as chief scientist in synthesizing the data, training new wellsitters, and participating in drilling decisions. A fourth member of the scientific team held primary responsibility for drilling decisions, based on scientific, engineering, permitting and budgetary considerations. Team members were housed at a single site nearby in order to facilitate communication. Twenty geoscientists served as team members during the 2 1/2 month operation.

Tonto Drilling Company of Salt Lake City, Utah, drilled both holes using a trailer - mounted Longyear 44. Tonto employed two drilling crews of 2 men each, plus a foreman. Water was pumped to both sites from Glass Creek and stored in a 23000 l tank.

The designs of the holes were similar. Upper hole sections were cored using HQ bits (97 mm) in hard rock and drilled with 3 7/8" tricone bits (98 mm) in soft rock to slant depths of 140 m and 243 m, respectively. The holes were then reamed with a 5 5/8" tricone bit (143 mm), cased with 4 1/2" (114 mm) O.D. casing, cemented, and blow out preventer equipment (BOPE) was installed. Following a BOPE test to 3.4 MPa witnessed by representatives of the Bureau of Land Management, coring ahead at HQ size resumed. The conduit hole was cased again and stepped to NX size (76 mm) at 373 m, the dike hole at 482 m. In both holes, the decision to case was based largely on instability of the open section and on anticipated remaining distance to the target. Advantages of stepping to NX include considerably greater penetration rate in hard rock and ease of handling the rods, a significant factor on a slant hole. The 76 mm diameter was maintained to the final slant depths of 624 m and 829 m. It had been anticipated from surface outcrops of competent granite that the holes would be stable at least in basement, and could be left open for logging and in situ stress measurements. Unfortunately, this proved not to be the case. The basement was highly fractured, commonly to rubble. Casing to total depth was thus required to preserve the holes.

Difficulties encountered in drilling can be attributed to the hard but highly fractured character of the rock, lack of fluid circulation. and the slanted orientation of the holes. In the conduit hole, the drill stem twisted off at the reamer shell at a hole depth of 363 m. This problem was solved by cementing the lost shell and bit in place and coring through them. Problems with the dike hole were more severe. The drill stem broke just above the core barrel when the hole reached 366 m. Efforts at fishing failed because mangled "ears" of the core tube protruded above the top of the barrel. While setting a wedge to deviate the hole from the lost stem section, the hole collapsed at 260 m, sticking the rods and ultimately resulting in loss of 98 m of rods, the wedge, and 116 m of hole. Resolution of this problem involved cutting the rods and setting a new wedge at 250 m.

A principal concern was hole trajectory because of the need to intersect relatively small targets. Consequently, single-shot orientation surveys were run at frequent intervals, generally every 60 m but more often when problems with orientation were identified and less often when the hole was seriously unstable and drilling operations could not be interrupted. Both holes deviated substantially from the straight line trajectory initially envisioned. The conduit hole steepened at a rate of $1.5^{o}/100$ m from an initial dip of 55^{o} and drifted to the right at a rate of $0.3^{o}/100$ m. The drift to the right was small compared to the presumed target size. Steepening of the hole increased the amount of drilling required to reach the target by 60 m. These results were taken into account in orienting the drill rig for the dike hole. An initial dip of 54^{o} was used instead of the previously planned 60^{o} to compensate for expected steepening of the hole and an initial lead of 2^{o} to the left of the desired azimuth was similarly selected. However, the hole steepened and drifted to the right at a much greater rate than the conduit hole. Remedial action was not taken because of unstable hole conditions. As a result, the hole did not pass beneath Dry Crater as originally planned.

Results

Perhaps the most surprising result of the 1984 drilling effort was that the igneous targets were intersected directly beneath their postulated surface expressions. The first hole entered the conduit beneath the edge of the central depression in the vent area of Obsidian Dome. The depression had been interpreted as marking the region where magma sagged back down the vent at the close of the eruption. The second hole, although deviating so that it passed 60 m north of the center of Dry Crater, nevertheless intersected a rhyolite intrusion beneath a line formed by Dry Crater, a suspected crater beneath the south end of Obsidian Dome, an extrusive linear ridge extending southward from the vent area on Obsidian Dome, and the central depression of the Dome (Fig. 1). Drill holes, of course, only sample three dimensional structures along lines, and thus data on the geometry of the intrusion is limited. We cannot yet offer a subsurface model which accounts for all the numerous volcanic features in the vicinity of Glass Creek. Nevertheless, these results indicate that the intrusive features which were sampled are essentially vertical structures, and that the conduit of Obsidian Dome is an enlarged portion of a rhyolite dike whose position is marked by the surface features discussed above. Such a relationship between conduits and dikes has been well documented for basaltic volcanoes (Delaney and

Pollard, 1982). The orientation of the dike, where penetrated by the holes, is rotated 8^{o} clockwise from the main trend of the Inyo Chain. This may reflect a local variation in the trend of the dike. Alternatively, Fink and Pollard (1983) have suggested that the dike broke into segments as it approached the surface and rotated clockwise in response to a vertically varying stress field, producing an en echelon pattern.

While the position of the intrusion was accurately foreseen from the surface geology, physical, chemical ,and thermal features of the intrusion could not have been predicted. It is evident from Figures 2 and 3 that the conduit is a much more complex structure than the dike. It is seven times wider and, unlike the dike which is free of xenolithic material, roughly one third of it contains abundant wallrock debris. Some of this debris occurs in breccias and some as apparent screens between rhyolite fingers. Yet Obsidian Dome, which emerged from the conduit, contains virtually no xenolithic material. Probably the considerable dimensions and structural complexity of the conduit developed during explosive venting, and the Dome, emplaced at the end of the episode, was fed by a restricted portion of the conduit after the outermost, xenolith-rich portion had become immobile.

There is no evidence as to how close the dike approached to the surface at Glass Creek, other than that it is 7.3 m thick at 640 m depth. How rhyolite magma, presumably laden with volatiles, could reach this shallow depth without fragmenting due to internal vapor pressure and erupting explosively is an interesting question. Certainly, a large quantity of gas must have escaped from the intrusion. It seems possible that the large overlying craters are in part a consequence of magmatic degassing, and not merely phreatic.

While the dike is free of wallrock fragments in the section sampled by the dike hole, the wallrock is not free of dike fragments. A 2 cm fragment of dike was found 40 cm horizontally outside the intrusion contact, mixed into highly brecciated granite. Similarly deformed host material was not found in the conduit hole, probably because it was removed during growth of the conduit. A large quantity of granitic debris was ejected during the explosive phase of the Obsidian Dome eruption. In addition to stirring of magmatic material into the deforming basement, fragments of dike magma were blown into fractures in the basement and quenched to glass. Many such fractures were encountered in the dike hole, some as far as 130 m horizontally from the dike. Clearly, the intrusive event caused significant disruption of the granite basement over a broad zone. Because the walls of the intrusion were not eroded during an eruptive phase, emplacement of the dike must have been accommodated by 7 m of east - west extension.

Much of the fractured character of the basement along the Inyo trend, however, must be attributed to long - term tectonic activity on the Sierra front. It appears likely that the dike hole traversed a broad zone of deformation associated with the

Hartley Springs Fault, rather than intersecting a clearly defined fault zone. Obviously, examination of competent basement outcrops at the surface yielded a highly misleading view of granite at depth. This fact should be kept in mind in interpreting geophysical data in the Long Valley area.

Temperatures measured in the dike hole are generally consistent with heat flow measurements in the Sierra block (Lachenbruch et al., 1976), while temperatures in the conduit hole are clearly anomalous (Fig. 4). Temperatures in the two holes appear related to the size of the intrusion where it was intersected rather than to depth or distance from the caldera. If so, this is the first observation of residual magmatic heat from a single intrusive event, and suggests that cooling of the 600 year - old body was primarily by conduction rather than convection.

Analysis of the core is only beginning. However, some early geochemical observations deserve brief mention at this time: 1. Extreme chemical variation was found within the conduit. This variation spans the entire range of composition observed in the three large 600 year - old Inyo Domes and indicates a mafic to silicic compositional trend during eruption (Stockman et al., 1984). 2. The scarcity of glass in the intrusion contrasts markedly with the high glass content of the extrusive Dome. The glass zone extends tens of meters into the Dome but only tens of centimeters into the dike. Thus, magma at depth crystallized at cooling rates that yielded glass in the Dome. This probably reflects the controlling effect of water content of melt upon crystallization behavior. 3. The distal section of the Dome sampled by the 1983 hole has a substantially lower bubble content than the proximal section sampled by the conduit hole (Westrich and Eichelberger, 1984), suggesting that degassing and bubble collapse continued as the flow moved along the surface.

Summary

The 1984 drilling results demonstrate the feasibility and usefulness of slant core holes targeted on the basis of surface geology in exploring the subvolcanic environment. The present holes provide the first direct links between glassy extrusive rocks and crystalline intrusions in a young volcanic system, and the first direct observations of an intrusion which is still cooling. The results have provided insights into the origin and "plumbing" of the Inyo chain, and are likely to advance our knowledge about the causes of, and subsurface processes associated with, explosive silicic volcanism. A more thorough assessment of the value of this kind of scientific drilling must await completion of the core, borehole, and geophysical studies now underway. It is anticipated that interpretations of dike geometry based on limited sampling provided by the holes can be extended laterally and downward by the use of seismic and electrical techniques. Such efforts will be important to the success of future deeper exploration of the Inyo - Long Valley system. The next drilling step, now in the proposal stage, is to core a slant hole into the Inyo Dike within the more geologically complex setting of Long Valley Caldera.

Acknowledgments

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Figures captions

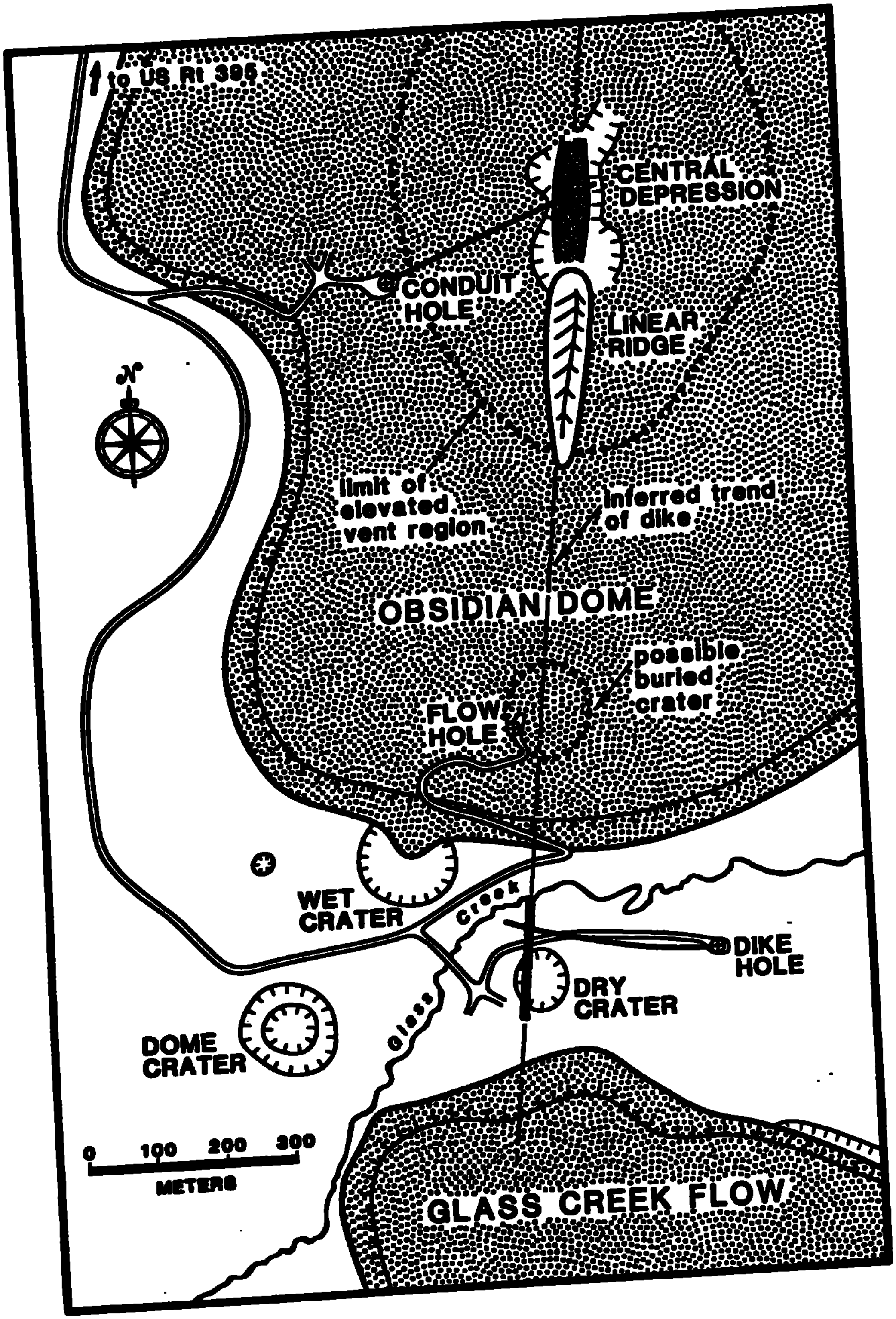
Figure 1. Map showing volcanic features of the Inyo chain in the vicinity of Glass Creek, and plan views of the core holes and intersected intrusions. The flow hole is a vertical hole drilled near the southern margin of Obsidian Dome in 1983. Surface structure, anomalous thickness of the flow, and the presence of 6 m of phreatic ejecta beneath the flow suggest that the hole may have intersected a buried phreatic crater, as indicated by the dashed circle. The conduit hole extends from outside the elevated vent region of the Dome and passes beneath a central depression, where it intersected the conduit as shown by the darkly shaded region. The dike hole slants west toward Dry Crater, a double phreatic crater with north - south elongation, and curves to the north. The position and width of the intersected rhyolite dike is indicated by the heavy black line. The orientation shown for the intersected bodies is based on the interpretation that they are connected along the indicated trend. Crater names are informal.

Figure 2. Cross section of the conduit of Obsidian Dome, showing the path of the conduit hole. The conduit is drawn assuming it is vertical, as discussed in the text. Tick marks along the hole mark slant depths. The final slant depth was 624 m with a right deviation of 5 m. Tv denotes precaldera basalt and KJg denotes Sierran granitic basement. Basalt adjacent to the conduit is shown as a dike, but this

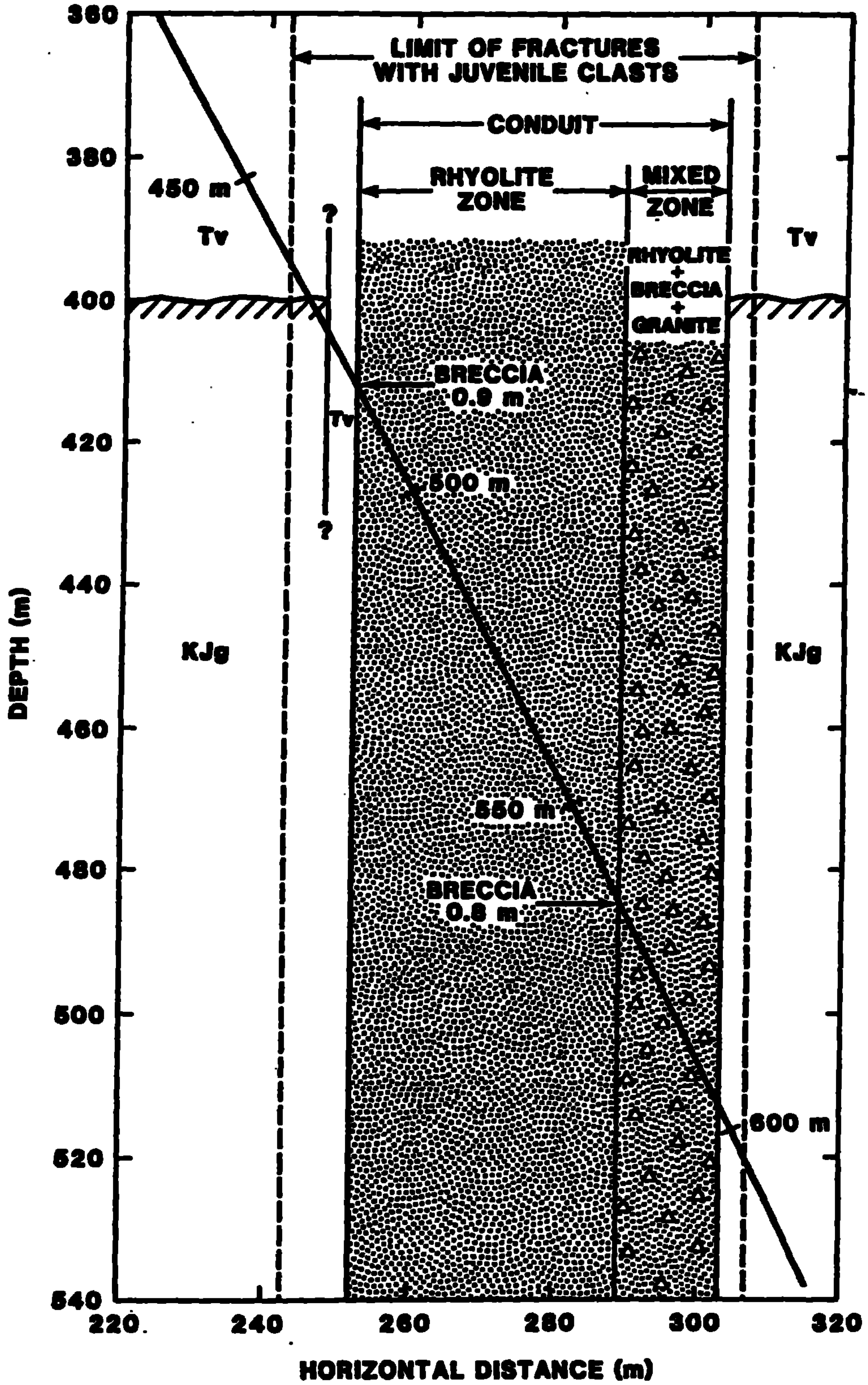
interpretation, which was made to explain the passage of the hole in and out of basement before hitting the conduit, is not certain. Individual units within the mixed zone of the conduit are too small to show at this scale. The rhyolite zone is apparently the feeder for Obsidian Dome, while the mixed zone developed during the earlier explosive phase.

Figure 3. Cross section of the rhyolite dike beneath Glass Creek, showing the path of the dike hole. Symbols are the same as in Figure 2. The final slant depth of the hole was 829 m, with a right deviation of 80 m. The width shown for the dike is based on the interpretation that the intersected body is near vertical and trends as shown in Figure 1.

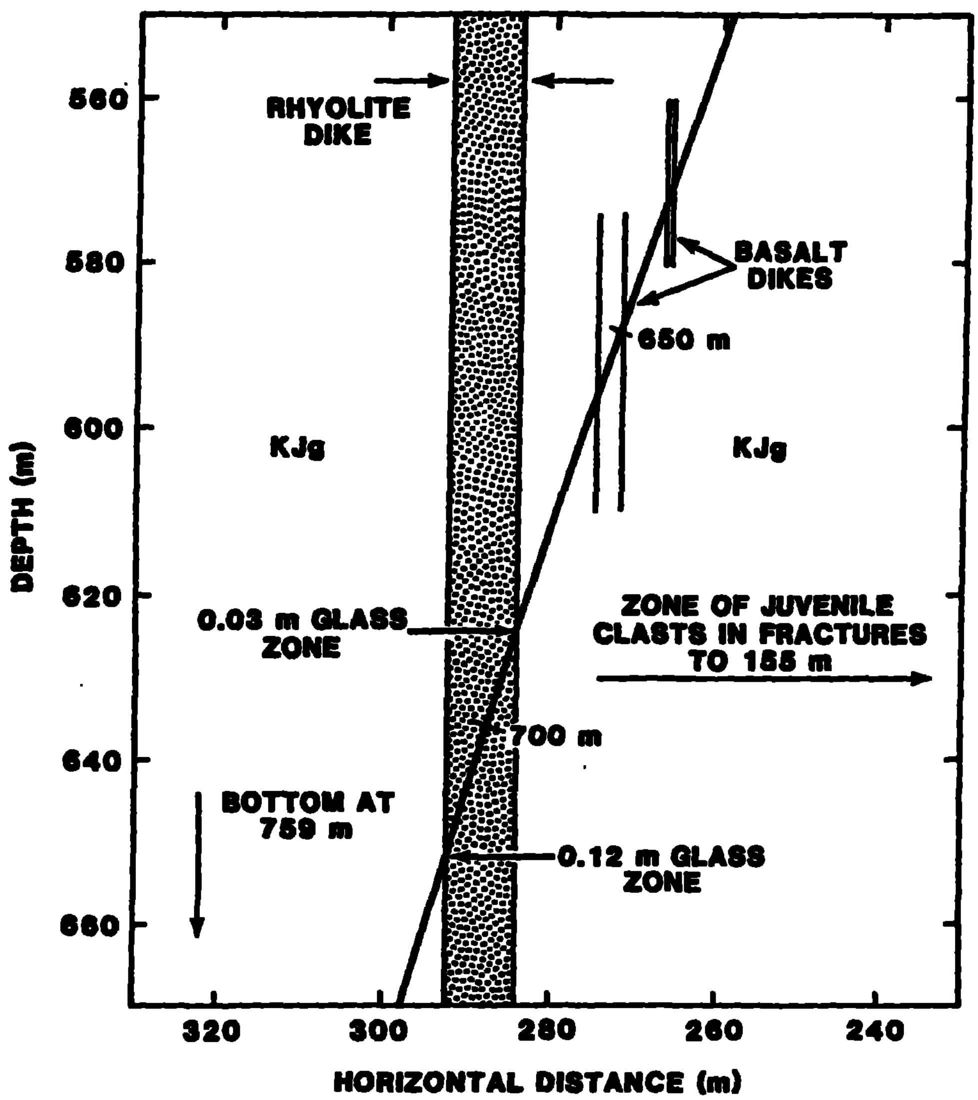
Figure 4. Temperature profiles for the conduit and dike holes (data from R. D. Meyer and L. C. Bartel, Sandia National Laboratories).



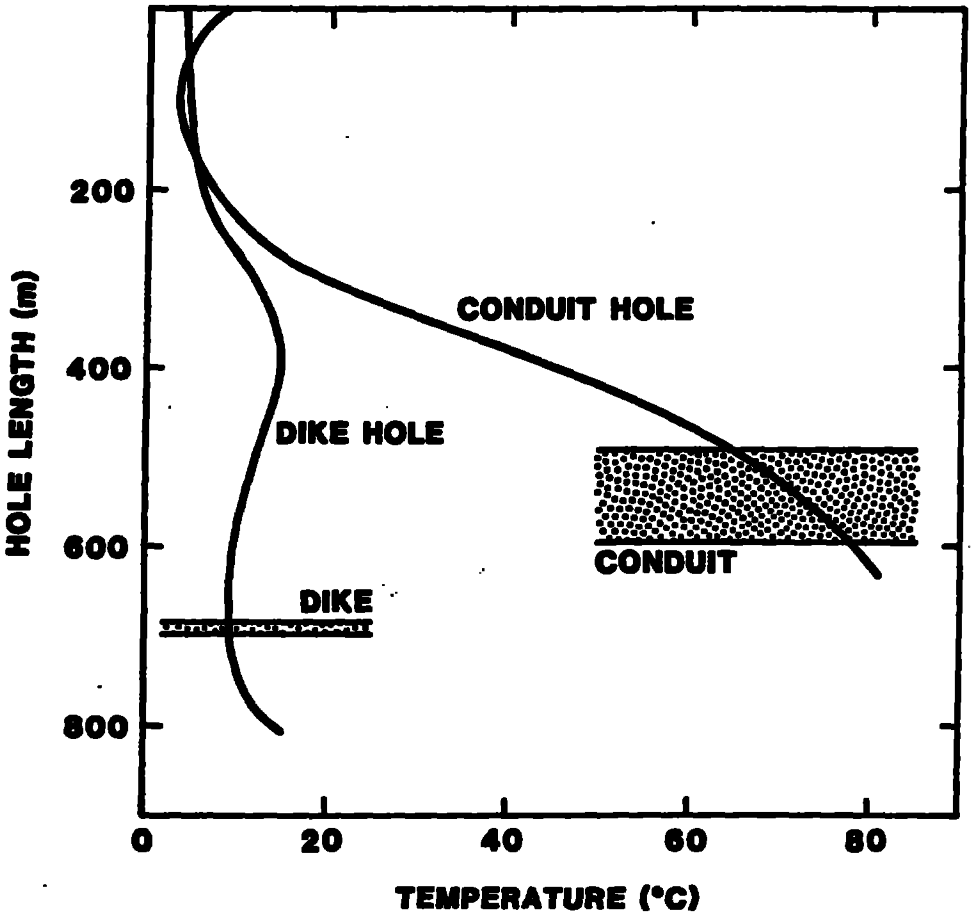
to US Rt 395
CENTRAL DEPRESSION
CONDUIT HOLE
LINEAR RIDGE
N
limit of elevated vent region
inferred trend of dike
OBSIDIAN DOME
possible buried crater
FLOW HOLE
WET CRATER
Glass Creek
DIKE HOLE
DRY CRATER
DOME CRATER
0 100 200 300
METERS
GLASS CREEK FLOW



LIMIT OF FRACTURES WITH JUVENILE CLASTS
CONDUIT
RHYOLITE ZONE
MIXED ZONE
RHYOLITE + BRECCIA + GRANITE
450 m
500 m
550 m
600 m
BRECCIA 0.9 m
BRECCIA 0.8 m
Tv
Tv
Tv
KJg
KJg
?
?
DEPTH (m)
HORIZONTAL DISTANCE (m)
360
380
400
420
440
460
480
500
520
540
220
240
260
280
300
320



RHYOLITE DIKE
BASALT DIKES
650 m
KJg
KJg
0.03 m GLASS ZONE
ZONE OF JUVENILE CLASTS IN FRACTURES TO 155 m
700 m
BOTTOM AT 759 m
0.12 m GLASS ZONE
560
580
600
620
640
660
DEPTH (m)
320
300
280
260
240
HORIZONTAL DISTANCE (m)


CONDUIT HOLE
DIKE HOLE
CONDUIT
DIKE
HOLE LENGTH (m)
200
400
600
800
0
20
40
60
80
TEMPERATURE (°C)